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MONOSTATIC MUELLER MATRIX LASER REFLECTOMETER

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Monostatic Mueller matrix laser reflectometer

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ABSTRACT

An instrument is described that operates as a true monostatic reflectometer. The instrument collects complete polarimetric information as well as reflectance. A beamsplitter at 45º to the incident and reflected beam allows monostatic operation. Complete polarimetric information in the form of Mueller matrices are measured by using a polarization state generator prior to the sample and a polarization state analyzer after reflection from the sample and beamsplitter. This Mueller matrix polarimeter is in the dual rotating retarder configuration. Two lasers currently serve as sources. The hardware and data reduction methods are discussed, and measurement results are given.

Keywords: Mueller matrix, reflectometer, polarized light, polarimeter

1. INTRODUCTION

Reflectance of a surface can be measured over an infinite set of combinations of geometries of the incident and reflected light beams. This infinite set can be subdivided into two sets, one that is all geometries but one, and the second that is the case when the incident light beam and the reflected light beam are coincident. The former is called the bistatic configuration and the latter is called the monostatic configuration. I will describe a reflectometer configured for the monostatic case in this paper. The monostatic case is of interest for any application where the light source issues from the same location at which the reflected signal is to be received.

In addition to this particular geometry, this reflectometer is notable because it measures the full Mueller matrix of the sample in reflection. The Mueller matrix is a 4×4 real matrix that contains all information concerning the polarization properties of a medium except the overall phase. In order to measure the Mueller matrix, there must be a polarization state generator on the incident side of the system and a polarization state analyzer on the output side of the system, and each of these must be able to generate all possible polarization states, i.e. they must be complete polarimeters. I use the dual rotating retarder configuration for this system as described in a previous paper[1]. In that previous work, a polarimeter was described for measuring bulk properties of materials in transmission. Azzam[2] originally formulated the dual rotating retarder method, and practical error compensation schemes are described by Goldstein and Chipman[3], and Chenault et al[4]. In addition to the errors of the polarimeter, nonideal behavior of the beamsplitter must be countered in the data reduction, and my method for accomplishing this will be explicitly described. A brief review of the Mueller matrix polarimeter will be given followed by a description of the instrumentation. Data reduction and error compensation is followed by presentation of some results.

2. DUAL ROTATING RETARDER MUELLER MATRIX POLARIMETER

A schematic diagram of the polarimetric reflectometer is shown in Fig. 1. A polarization state generator, consisting of a fixed linear polarizer followed by a rotating retarder, produces a set of polarization states to be sent to the sample. Following reflection from the sample, the beam passes through a polarization state analyzer that consists of a rotating retarder and a fixed linear polarizer. The two retarders are rotated at different but harmonic rates, and a modulation of the detected intensity results. The Mueller matrix of the sample is found through a relationship between the Fourier coefficients of a series representing the modulation and the elements of the sample matrix.

The fixed linear polarizers are aligned with each other and the polarization of the source. The second retarder is rotated at a rate five times that of the first. This generates twelve harmonic frequencies in the Fourier spectrum of the modulated intensity. This 5:1 rotation ratio is not the only ratio that can be used to determine Mueller matrix elements, but it is the lowest ratio in which the expressions for the Fourier coefficients may be inverted to give the Mueller matrix elements.

The retarders used in this system are nominally quarter wave zero order retarders. Retarders of almost any retardation value may be used, however the intensity modulation that results with quarter wave retarders contains null points so the modulation is deeper. Sabatke et al[5] and Tyo[6] have shown that retarders having retardance of approximately 132° are optimal in terms of signal-to-noise and insensitivity to element misalignment, but retarders with this value do not yet have off-the-shelf availability.
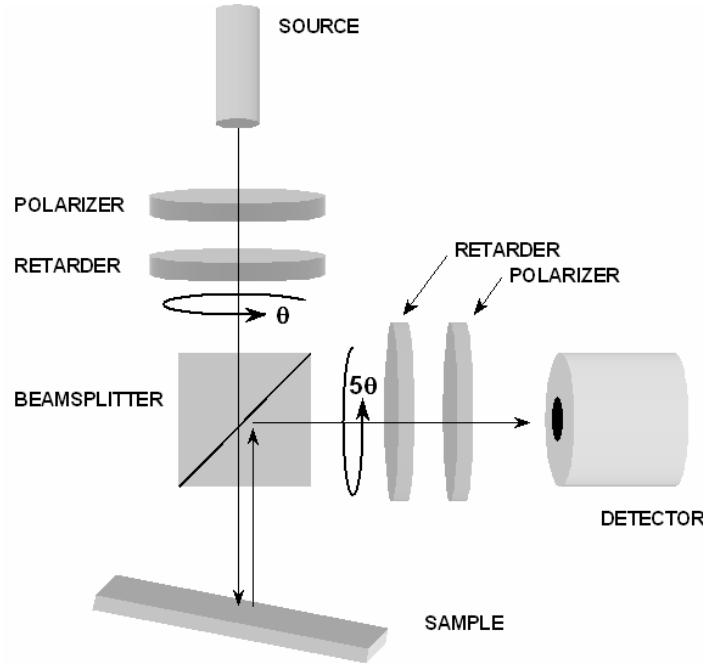

Figure 1. Schematic diagram of the monostatic reflectometer.

The Mueller matrix for the system is

$$\mathbf{P}_2\mathbf{R}_2(\theta)\mathbf{M}\mathbf{R}_1\mathbf{P}_1 \qquad\qquad (1)$$

where $\mathbf{P}$ indicates a linear polarizer, $\mathbf{R}(\theta)$ indicates an orientation-dependent linear retarder, and $\mathbf{M}$ represents the sample Mueller matrix. The detected intensity is given by

$$I = c\mathbf{A}\mathbf{M}\mathbf{P} \qquad\qquad (2)$$

where $\mathbf{P} = \mathbf{R}_1\mathbf{P}_1\mathbf{S}$ is the Stokes vector of light leaving the polarization state generator ($\mathbf{S}$ is the Stokes vector of the light from the source), $\mathbf{A} = \mathbf{P}_2\mathbf{R}_2$ is the Mueller matrix of the polarization state analyzer, $\mathbf{M}$ is the Mueller matrix of the sample, and c is a proportionality constant obtained from the absolute intensity.

Intensity values in the form of voltages are measured as the retarders are incrementally advanced such that the first retarder rotates through 180°. The Fourier coefficients are then obtained from the measured intensity values. There are twelve frequencies relating to the angle of the fast axis of the retarders, and so there are 25 Fourier coefficients. The minimum number of equations needed to solve for the coefficients is 25 so that the maximum rotational increment for the first retarder is 7.2°.

There are generally five errors in this system that should be considered. These are the orientational errors of the two retarders and the last polarizer with respect to the first polarizer, and the errors in retardation of the two retarders from nominal values. Diattenuation in the retarders and retardation in the polarizers could also be sources of error, but experimental experience and simulations have shown that these are secondary errors that can be ignored in practice.

Additional details of the mathematics of the system, including the error compensation are given in Goldstein[1], Goldstein and Chipman[3], and Chenault et al[4].

3. MUELLER MATRIX REFLECTOMETER

The reflectometer is set up on a rail system and the main beam path is vertical just as shown in Fig. 1. A photograph of the reflectometer is presented in Fig. 2. Lasers are oriented horizontally on a shelf at the top of the rail system, and the beam is brought down the front of the rail system with mirrors. The beam passes through a chopper and polarization optics that produce linear polarization aligned with the first polarizer of the Mueller matrix polarimeter. The beam then passes through the polarization state generator and the beamsplitter before striking the sample. The sample is located on a rotation stage such that the location at which the laser beam is incident is the center of rotation. The beam reflected from the sample then goes back to the beamsplitter where a portion of the sample reflection is directed toward the polarization state analyzer. It is important to dump the portion of the beam that exits the beamsplitter to the left in Fig. 1 as completely as possible so that the detector sees the desired signal beam and not the dumped beam. It is also important to shield the system, particularly the final detector, from stray light. There are many surfaces in the system, and there are portions of the laser beam scattered throughout the environment.

Figure 2. Photograph of the monostatic reflectometer.

A diagram that includes the electronic devices and data paths is shown in Fig. 3. A LabVIEW program controls the operation of the instrument. There are two rotary stage controllers connected to the computer, one that controls movement of the four rotary stages holding the Mueller matrix polarimeter polarization elements, and another that controls the position of the sample stage. A chopper reference signal as well as the signal from the detector is sent to a lock-in amplifier. The output from the lock-in is sent to a digital acquisition card in the computer.

There are several parameters that can be set in the LabVIEW program, most notably the set of positions of the sample. Once these are set and the program started, the system runs unattended as long as required. The data is saved in a text file at the end of the run.
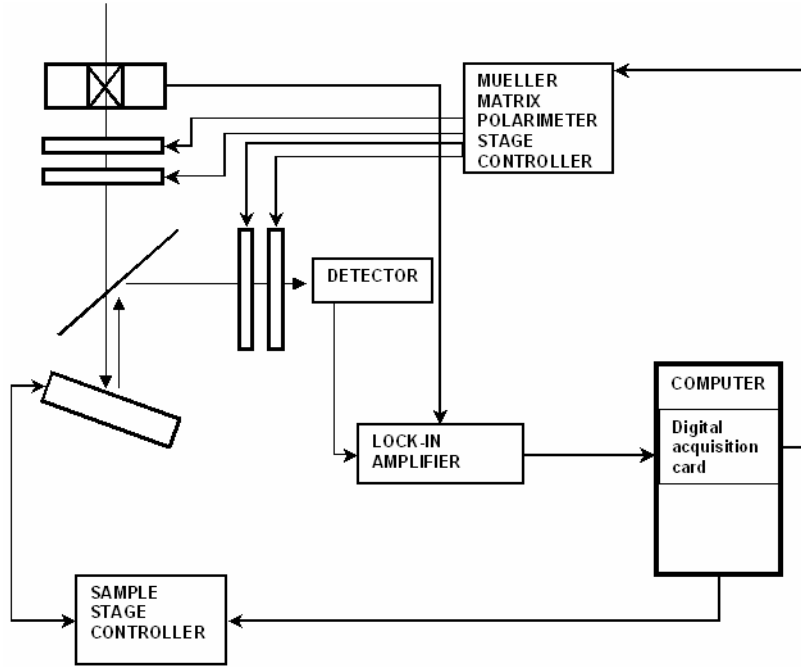
Figure 3. System electronics and data paths

4. DATA REDUCTION AND ERROR COMPENSATION

Although the beamsplitter indicated in Fig. 1 is a cube, a better solution is to use a plate because the reflections from cube surfaces normal to the beam increase the stray light getting to the detector. With either cube or plate types, there is no off-the-shelf beamsplitter known to this author that does not introduce retardance. Beamsplitters that produce a 50/50 split with no retardance have been designed[7], but they have not yet been fabricated. Because of this residual retardance in the beamsplitter, the measured Mueller matrix will contain a retardance that is not associated with the sample. This must be removed to obtain the true Mueller matrix of the sample.

The apparent measured Mueller matrix of the sample is the product of three component Mueller matrices. In order of light transmission, these are 1) the Mueller matrix of the beamsplitter in transmission, 2) the Mueller matrix of the sample, and 3) the Mueller matrix of the beamsplitter in reflection on the beam reflection from the sample. The measured Mueller matrix can then be expressed as

$$M_{measured} = M_{BSR} M_S M_{BST} \qquad (3)$$

where the subscript BSR indicates the beamsplitter in reflection and the subscript BST indicates the beamsplitter in transmission. The true Mueller matrix of the sample can be found by solving the equation for M_S so that

$$M_S = M_{BSR}^{-1} M_{measured} M_{BST}^{-1} . \qquad (4)$$

M_{BST} can be measured directly by removing the sample stage and placing the polarization state analyzer in line with the original beam, as shown in Fig. 4. M_{BSR} is found indirectly. The sample is replaced by a high-quality front surface aluminum mirror placed normally to the beam in the original instrument configuration as in Figure 1. The Mueller matrix for an ideal mirror is

$$M_M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}. \qquad (5)$$

M_{BSR} is then

$$M_{BSR} = M_T M_{BST}^{-1} M_M^{-1} \qquad (6)$$

where M_T is the measured Mueller matrix through the whole system with the mirror in the sample position. Measured retardances on the order of 15° have been found for commercial 50/50 beamsplitters designed to be nonpolarizing and used at 45°. For the plate beamsplitter used here, a retardance of this magnitude was found to be almost equally distributed between the initial path through the beamsplitter and the reflection to the polarization state analyzer.

Having established the beamsplitter retardances, the polarimetric reflectometer is operated and saves the data that has been corrected for Mueller matrix polarimeter errors as described in Section 2. The data is then compensated for beamsplitter retardances in a Mathcad program that also plots the data. Tests have been performed with the mirror and other samples to insure that residual retardance all originate from the beamsplitter.
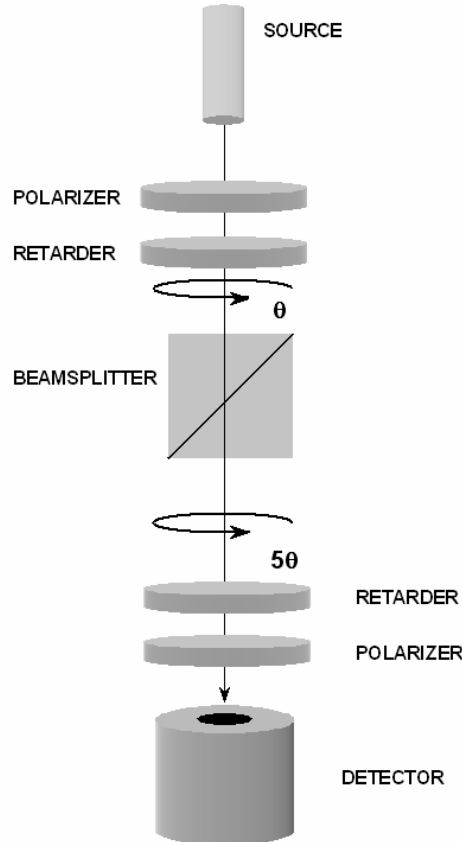

Figure 4. Configuration for measurement of transmission retardance of beamsplitter.

5. MEASUREMENT RESULTS

While many samples have been measured since this instrument has been constructed, I show three examples in Figs. 5-10. These measurements were all taken with the 1.06µm source. The samples are oriented with respect to the incident beam from 75° on one side of normal incidence to 10° on the other so that the behavior around normal incidence as well as behavior at high incidence angles is captured. The three samples are aluminum panels painted with three different Federal standard paints, gloss white, tan, and flat white. The tan paint is a semi-gloss, so that three levels of gloss are represented. Figs. 5, 7, and 9 are reflectance curves, and Figs. 6, 8, and 10 are the Mueller matrices.
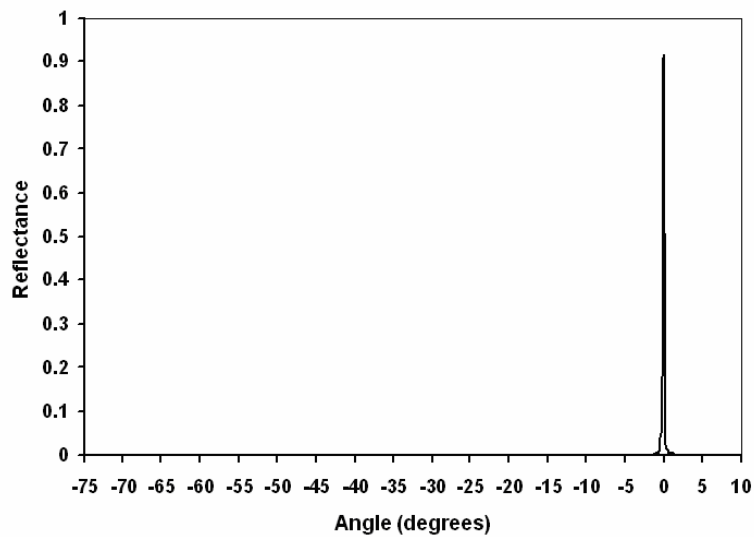
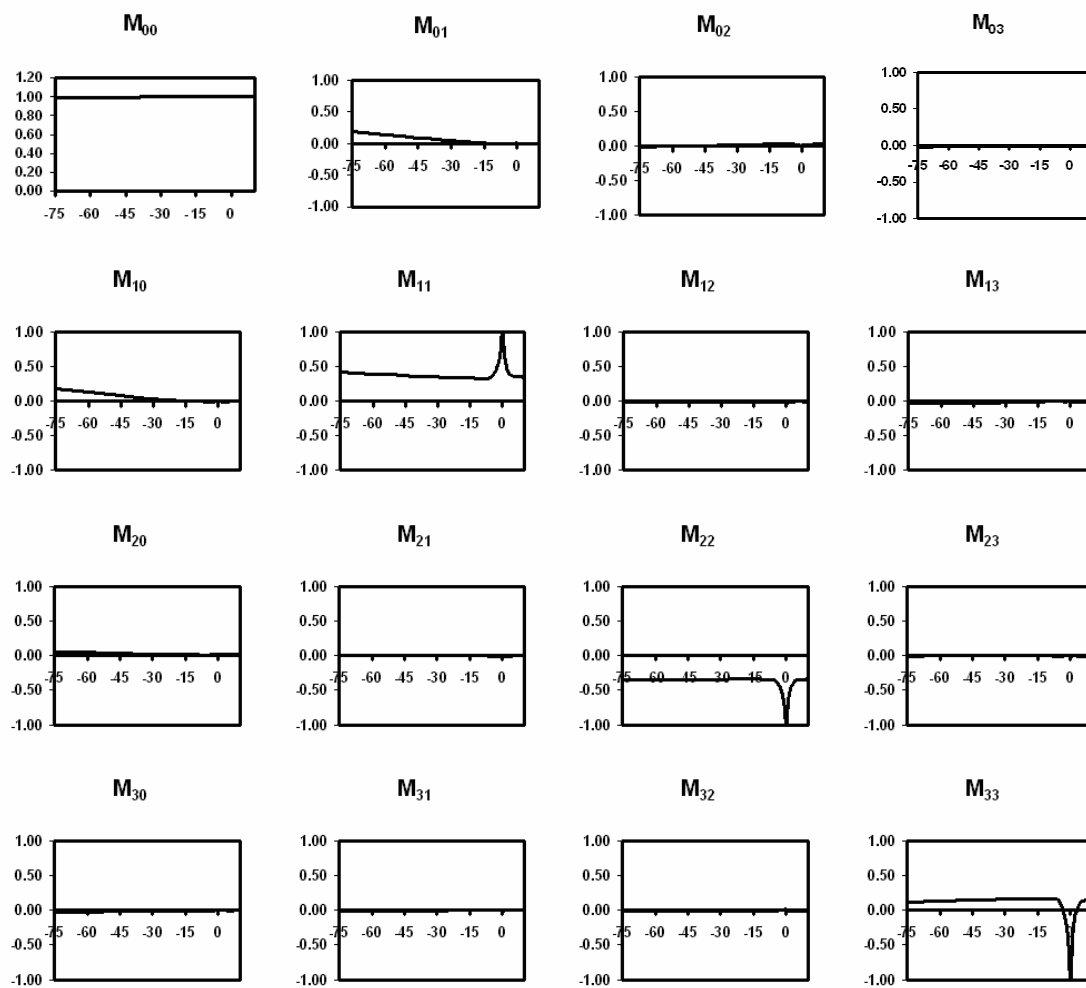Figure 5. Reflectance vs. sample angle for Federal standard gloss white.

Figure 6. Mueller matrix vs. sample angle for Federal standard gloss white
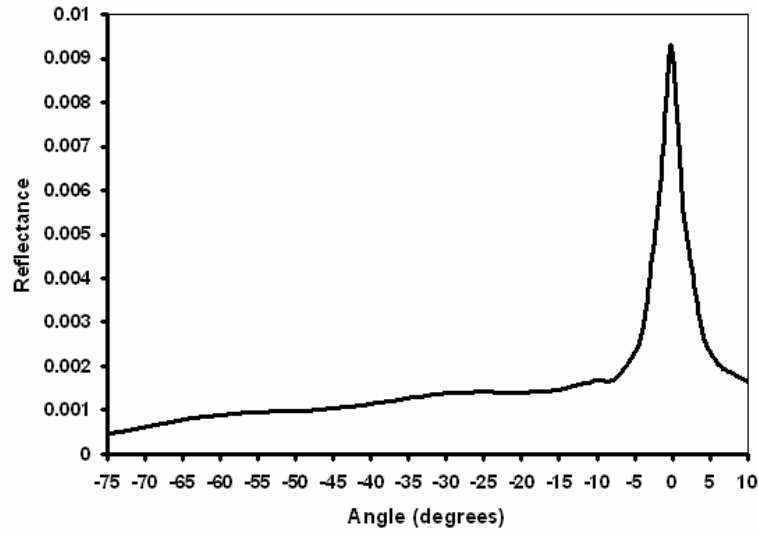
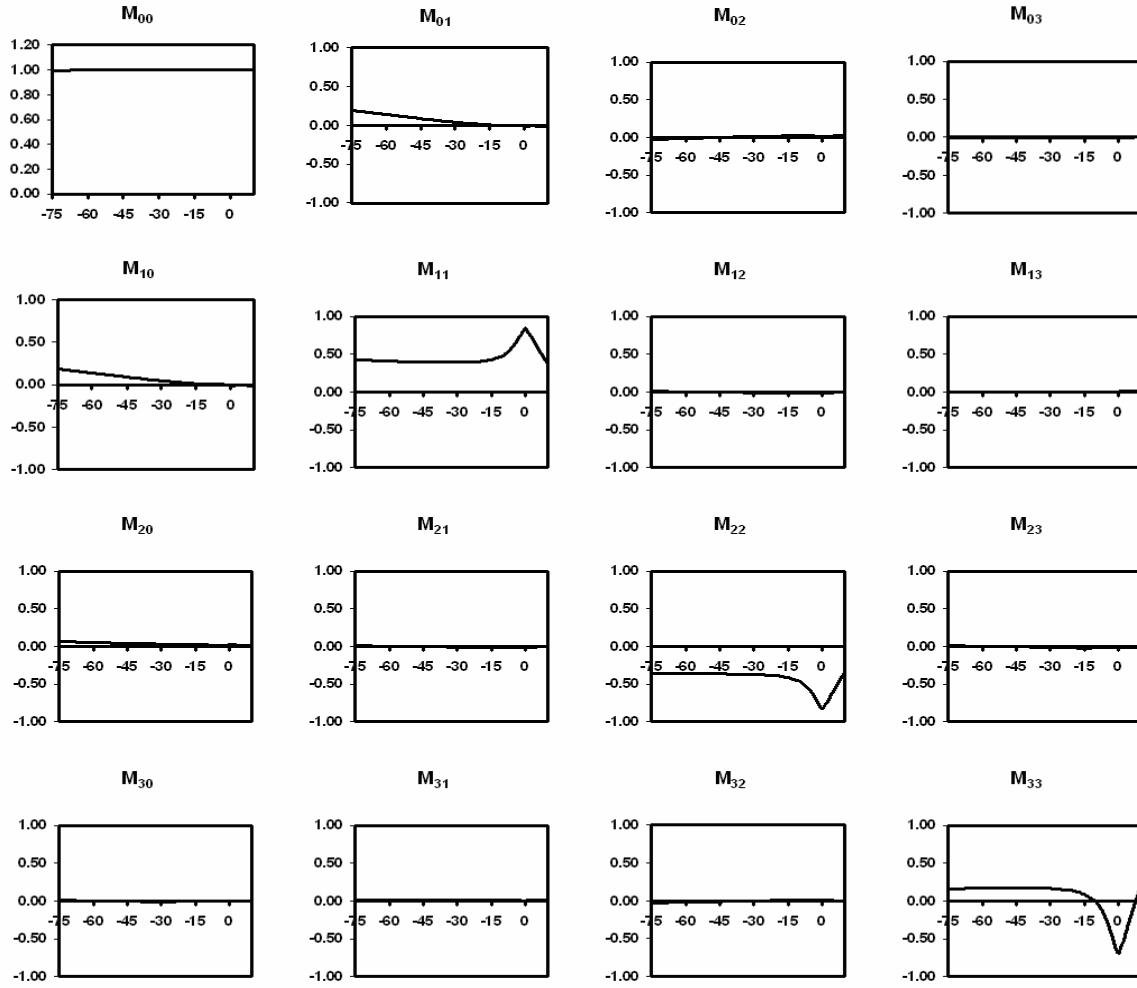Figure 7. Reflectance vs. sample angle for Federal standard tan.

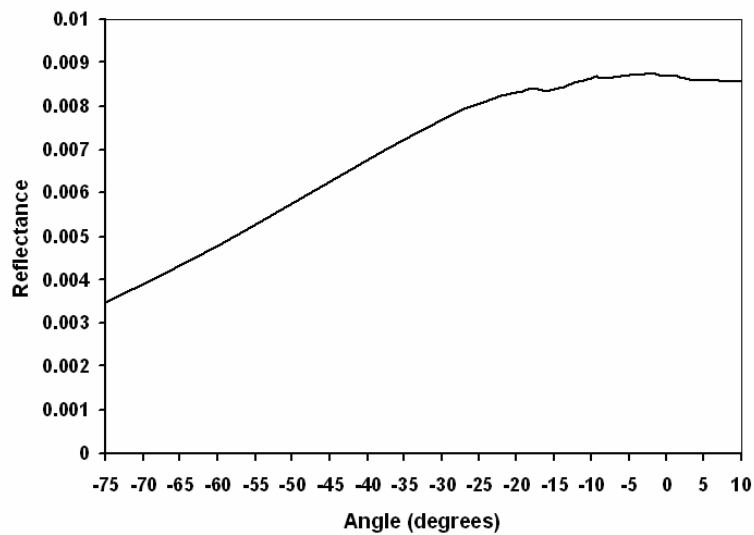Figure 8. Mueller matrix vs. sample angle for Federal standard tan

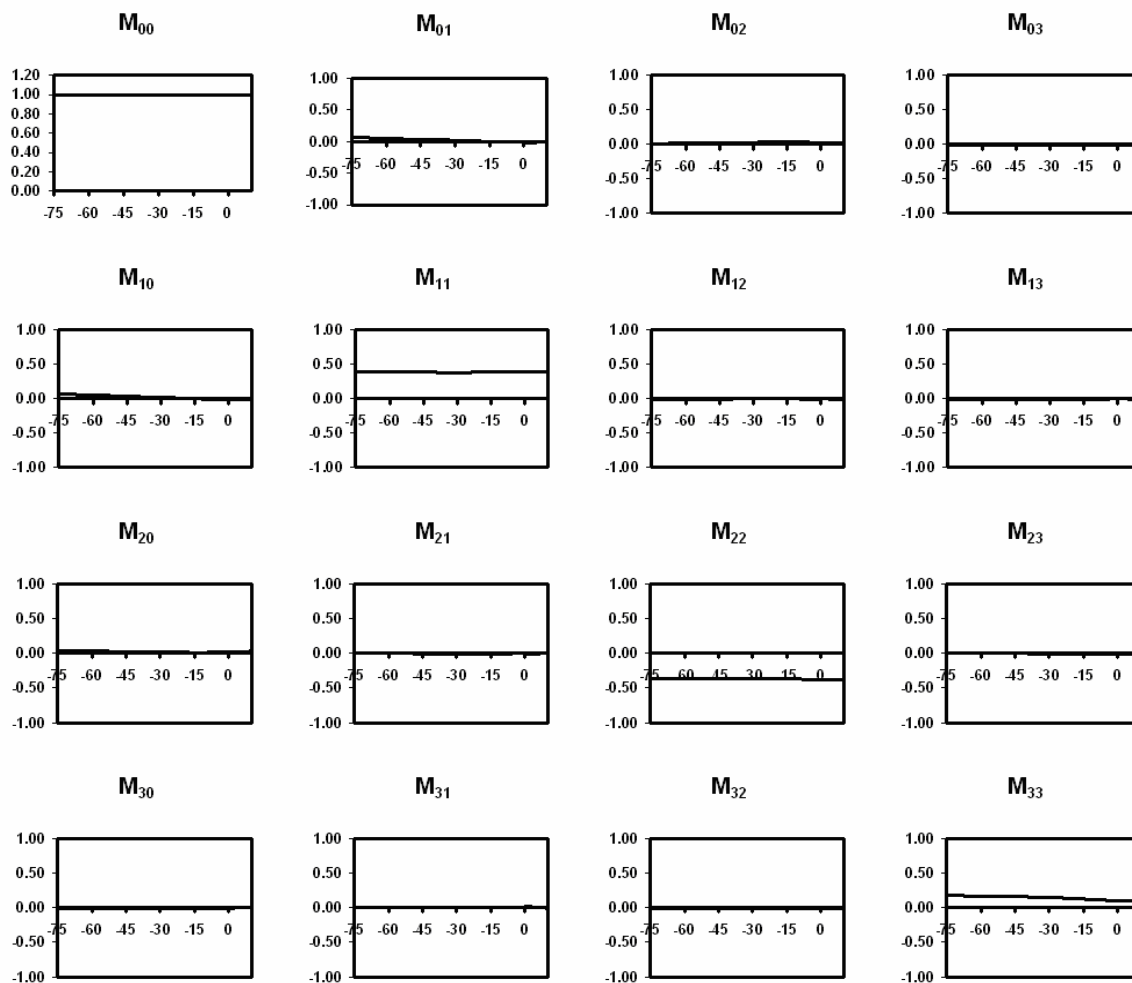Figure 9. Reflectance vs. sample angle for Federal standard flat white

Figure 10. Mueller matrix vs. sample angle for Federal standard flat white

6. DISCUSSION

The reflectance curves in Figs. 5, 7, and 9 make clear the difference between the gloss of the samples. The gloss white reflectance curve energy is localized around normal incidence, the tan reflectance curve is still fairly sharp near normal incidence, and the flat white reflectance curve is a very broad distribution centered around normal incidence. The normalized Mueller matrices represent these three levels of gloss as well. The matrix for gloss white has a sharp peak at normal incidence, where the diagonal elements of the matrix take on values near ±1 and off-diagonal elements are near 0. The matrix at normal incidence has the form of the Mueller matrix of a mirror, and this is to be expected for a very shiny surface. The matrix for the tan sample approaches this behavior, but is not quite as good of a mirror and so at normal incidence looks like a mirror that also absorbs in all polarization states. Note that the M_{01} and M_{10} elements of the matrix have finite values for high incidence angles; this is particularly obvious for gloss white and tan. These elements represent a linear horizontal diattenuation and polarizance, and this behavior is typical for shiny surfaces at high angles of incidence. The Mueller matrix for flat white shows fairly constant values over the whole range of angles with off-diagonal elements near 0 everywhere.

A reflectometer has been described, and experimental reflectance and Mueller matrix results have been presented. Three samples illustrative of three levels of gloss were measured. Many more samples have been measured, but these will be the subject of future reports.

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